REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
July 4, 1995

3. REPORT TYPE AND DATES COVERED
Final: March 1, 1992-April 30, 1995

4. TITLE AND SUBTITLE
Grid Amplifiers

5. FUNDING NUMBERS
DAAL03-92-G-0032

6. AUTHOR(S)
David Rutledge

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Caltech, Pasadena, CA 91125

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
ARO 29523.24-EL

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

ABSTRACT (*Maximum 200 words*)

Quasi-optical power combining allows the combining of a large number of devices in free space without the usual transmission-line combiner losses. It is a particularly attractive idea at millimeter-wavelengths, where the devices can be made as a monolithic integrated circuit. During this contract we demonstrated the following significant "firsts"—

1. Monolithic quasi-optical millimeter-wave oscillator—35 GHz
2. Quasi-optical oscillator with signicant power—10 W
3. Large-scale quasi-optical amplifier—200 devices
4. Quasi-optical amplifier with significant power—3.8 W
5. Monolithic millimeter-wave quasi-optical amplifiers with gain—5 dB at 40 GHz and 50 GHz. The saturated output power of the 40-GHz amplifier is 400 mW.

14. SUBJECT TERMS
Millimeter-wave systems, grid oscillators, grid amplifiers.

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

Final Report
Grid Amplifiers

David Rutledge
California Institute of Technology

March 1, 1992 through April 30, 1995

Contract DAAL03-92-G-0032

Grid Amplifiers

Solid-state devices have quite limited power outputs at microwave and millimeter-wave frequencies. To provide sufficient power for radar and communications transmitters, the outputs of many transistors need to be combined. Quasi-optical power combiners that combine the output power in free space are attractive for high-power circuits because they avoid the losses associated with transmission-line power combiners. The quasi-optical approach is suitable for millimeter waves because the spacing is small enough that the device can be made as a monolithic integrated circuit. In previous work in our group and other groups, many different quasi-optical devices, including oscillators, amplifiers, phase shifters, mixers, and multipliers have been demonstrated. Our research goals in this contract were using a large number of devices in an amplifier (of the order of one hundred), achieving substantial power outputs (1 Watt or larger), demonstrating monolithic quasi-optical devices, and pushing the output to frequencies above 300 GHz. During this contract, our group made progress in all these areas, establishing the following "firsts"—

1. Monolithic quasi-optical millimeter-wave oscillator—35 GHz.
2. Quasi-optical oscillator with signicant power—10 W at 10 GHz.
3. Large-scale quasi-optical amplifier—Grid amplifier with 200 transistors at 10 GHz.
4. Demonstration of a diode-grid frequency doubler with a 300-μW output at 1 THz.
5. Quasi-optical amplifier with significant power—3.8 W HEMT grid amplifier.
6. Monolithic millimeter-wave quasi-optical amplifiers with gain—5 dB at 40 GHz and 50 GHz. The saturated output power of the 40-GHz amplifier is 400 mW.

The first four projects have been described in previous annual reports. The recent results are described below.

High-Power pHEMT Grid Amplifier

We have fabricated a 100-element hybrid grid amplifier with custom-made pHEMT differential amplifier chips made by Lockheed-Martin Laboratories. The grid is stabilized against spurious oscillations by resistors in the gate. The grid shows a peak gain of 12/ts dB at 9 GHz with a 3-dB bandwidth of 15%. The noise figure is 3 dB, and the saturated output power is 3.7 W. These figures are a considerable advance over previous quasi-optical amplifiers. A paper describing the grid has been submitted to *IEEE Transactions on Microwave Theory and Techniques.*

A 40-GHz Monolithic HBT Grid Amplifier

A 36-element monolithic grid amplifier has been fabricated by Rockwell International. The active elements are pairs of heterojunction-bipolar-transistors. The peak gain is

5 dB at 40-GHz. The saturated output power is 400 mW. This is the first report of a monolithic quasi-optical power amplifier. All previous reports have been in hybrid circuits. A paper describing the grid has been submitted to *IEEE Microwave and Guided Wave Letters.* In this paper, the gain was reported as 4 dB. We have improved this result by 1 dB since that time.

A 50-GHz Monolithic pHEMT Grid Amplifier

We have recently begun testing a 36-element monolithic grid amplifier fabricated by Lockheed-Martin. The active elements are pairs of pseudomorphic HEMT devices. The preliminary gain is 5 dB at 50 GHz (See the Figure). The ON-OFF ratio (comparison with the un-biased grid is 27 dB. We believe this is the first time that gain has been seen in a quasi-optical monolithic pHEMT grid amplifier.

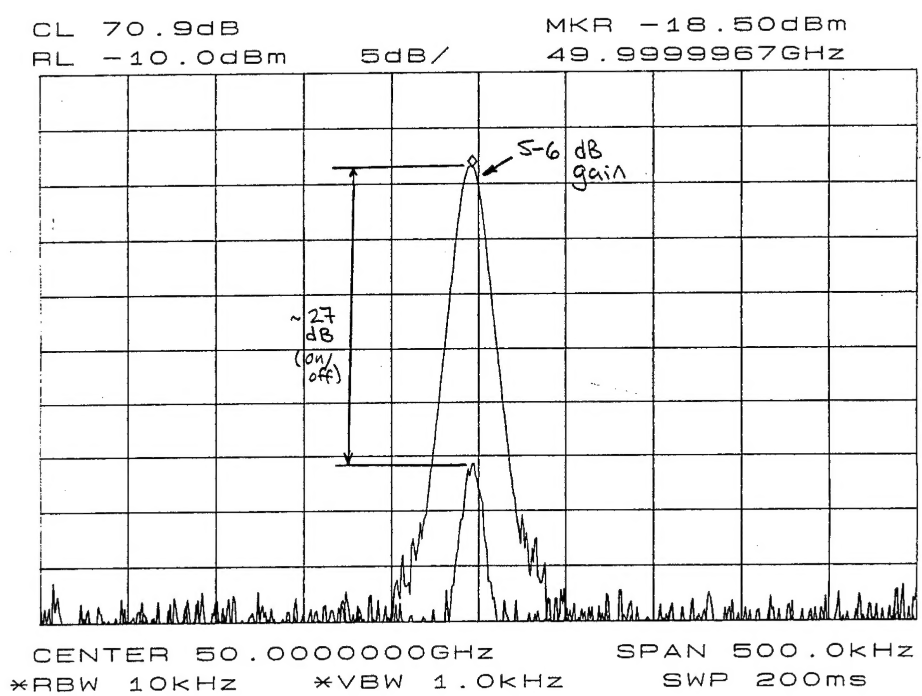

Figure. Spectrum analyzer plot of output from a 50-GHz pHEMT monolithic grid amplifier. The top trace is the signal when the bias is turned on. The bottom trace is with the signal off. The gain is 5 dB, and the on-off ratio is 27 dB.

Publications

[1] "A 100-Element Planar Schottky Diode Grid Mixer," Jonathan B. Hacker, Robert M. Weikle, II, Moonil Kim, Michael P. DeLisio, and David B. Rutledge, *IEEE Transactions on Microwave Theory and Techniques, MTT40,* pp. 557–562, 1992.

[2] "New Concepts for High Frequency and High Power Frequency Multipliers and Their Impact on Quasi-Optical Monolithic Array Design," H.-X. L. King, L. B. Sjogren, N. C. Luhmann, Jr., and D. B. Rutledge, *Int. J. of Infrared and Millimeter Waves, 13*, 1992, pp. 251–266.

[3] "Integrated horn antennas for millimeter-wave applications," G. M. Rebeiz and David B. Rutledge, *Annales des Télécommunications 47,* 1992, pp. 38–48.

[4] "Quasi-Optical Solid-State Microwave Sources," Jonathan B. Hacker, Robert M. Weikle, Moonil Kim, Michael P. DeLisio, and David B. Rutledge, Third SPIE Conference on Intense Microwave and Particle Beams, Los Angeles, CA, January, 1992.

[5] "Broadband Millimeter-Wave GaAs Transmitters and Receivers using Planar Bow-Tie Antennas," Y. Konishi, M. Kamegawa, M. Case, R. Yu, M. J. W. Rodwell, and D. B. Rutledge, 3rd International Symposium on Space Terahertz Technology, Ann Arbor, Michigan, March 24–26, 1992.

[6] "Oscillator and Amplifier Grids," David B. Rutledge, Jonathan B. Hacker, Moonil Kim, Robert M. Weikle II, R. Peter Smith, and Emilio Sovero, IEEE MTT International Symposium, Albuquerque, NM, June, 1992.

[7] "Probe Modelling for Millimeter-Wave Integrated-Circuit Horn Antennas," Yong Guo, Jung-Chih Chiao, Kent A. Potter, and David B. Rutledge, IEEE AP-S International Symposium, Chicago, IL, July 18–25, 1992.

[8] "A Millimeter-Wave Slot-V Antenna," Alina Moussessian and David B. Rutledge, IEEE AP-S International Symposium, Chicago, IL, July 18–25, 1992.

[9] "Quasi-optical antenna-mixer-array design for terahertz frequencies," Yong Guo, Kent Potter, and David Rutedge, 3rd International Symposium on Space Terahertz Technology, Ann Arbor, Michigan, March 24–26, 1992.

[10] "Oscillator and amplifier grids," David Rutledge, Jonathan B. Hacker, Moonil Kim, R. Peter Smith, Emilio Sovero, IEEE MTT Symposium, Albuquerque, NM, June 1992.

[11] "Active grids for quasi-optical power combining," Moonil Kim, Jon Hacker, David Rutledge, Emilio Sovero, James Rosenberg, 2nd International Workshop of the German IEEE MTT/AP joint chapter on Integrated Nonlinear Microwave and Millimeter Wave Integrated Circuits, Duisburg, Germany, October 1992.

[12] "Planar MESFET Grid Oscillators using Gate Feedback," Robert M. Weikle, II, Moonil Kim, Jonathan B. Hacker, Michael P. DeLisio, David B. Rutledge, *IEEE Transactions on Microwave Theory and Techniques, MTT40,* pp. 1997–2003, 1992.

[13] "Transistor Oscillator and Amplifier Grids," Robert M. Weikle, II, Moonil Kim, Jonathan B. Hacker, Michael P. DeLisio, David B. Rutledge, *Proceedings of the IEEE, 80,* pp. 1800–1809, 1992.

[14] "Wave Techniques for Noise Modeling and Measurement," Scott W. Wedge and David B. Rutledge, *IEEE Transactions on Microwave Theory and Techniques, MTT40*, pp. 2004–2012, 1992.

[15] "Active grids for quasi-optical power combining," Moonil Kim, Jon Hacker, David Rutledge, Emilio Soverro, James Rosenberg, 2nd International Workshop of the German IEEE MTT/AP joint chapter on Integrated Nonlinear Microwave and Millimeter Wave Integrated Circuits, Duisburg, Germany, October 1992.

[16] "A 35 GHz HBT monolithic grid oscillator," Moonil Kim, Emilio Sovero, Robert Weikle, Jonathan Hacker, Michael De Lisio, and David Rutledge, 17th International Conference on Infrared and Millimeter Waves, Pasadena CA, December 1992.

[17] "Microswitch beam-steering grid," Jung-Chih Chiao and David Rutledge, 17th International Conference on Infrared and Millimeter Waves, Pasadena CA, December 1992.

[18] "Grid Amplifiers," Ph.D. Thesis by Moonil Kim, Caltech, Pasadena, CA, 91125.

[19] "A 100-element HBT grid amplifier," Moonil Kim, Emilio Sovero, Jon Hacker, Michael DeLisio, Jung-Chih Chiao, Shi-Jie Li, David Gagnon, James Rosenberg, and David Rutledge, *IEEE Trans. Microwave Theory and Techniques, MTT-41*, pp. 1762–1771, October 1993.

[20] "A 6.5 GHz–11.5 GHz using a grid amplifier with external feedback," Moonil Kim, Emilio Sovero, Jonathan Hacker, Michael DeLisio, James Rosenberg, and David Rutledge, *IEEE Transactions on Microwave Theory and Techniques, MTT-41*, pp. 1772–1774, October 1993.

[21] "A 100-element HBT grid amplifier," Moonil Kim, Emilio Sovero, Jonathan Hacker, Michael DeLisio, Jung-Chih Chiao, Shi-Jie Li, David Gagnon, James Rosenberg, and David Rutledge, IEEE International Microwave Symposium, Atlanta GA, June 1993.

[22] "A 100-element HBT grid amplifier," Moonil Kim, Emilio Sovero, Jonathan Hacker, Michael DeLisio, Jung-Chih Chiao, Shi-Jie Li, David Gagnon, James Rosenberg, and David Rutledge, PIERS, Pasadena, CA, July 1993.

[23] "Active Grids for Quasi-Optical Power Combining," James Mink and David Rutledge, General Assembly of URSI, Kyoto, Japan, August 1992

[24] "Performance of a 100-element HBT grid amplifier," Moonil Kim, Emilio Sovero, Jonathan Hacker, Michael DeLisio, Jung-Chih Chiao, Shi-Jie Li, David Gagnon, James Rosenberg, and David Rutledge, European Microwave Conference, Madrid, September 1993.

[25] "Performance and applications of a 100-element HBT grid amplifier," Moonil Kim, Emilio Sovero, Jonathan Hacker, Michael DeLisio, Jung-Chih Chiao, Shi-Jie Li,

David Gagnon, James Rosenberg, and David Rutledge, the Asia-Pacific Microwave Conference, Hsinchu, Taiwan, October 1993.

[26] "Performance of a 100-element HBT grid amplifier," David Rutledge, Moonil Kim, Emilio Sovero, Michael DeLisio, Jonathan Hacker, Jung-Chih Chaio, Shi-Jie Li, David R. Gagnon, and James J. Rosenberg, International Device Research Symposium, Charlottesville, VA, November 1993.

[27] "Microswitch Beam-Steering Grid," Jung-Chih Chiao and David B. Rutledge, International Conference on Millimeter and Submillimeter Waves and Applications, San Diego, CA January 1994.

[28] "Millimeter-wave performance of a sliding planar backshort," Victor M. Lubecke, William R. McGrath, and David B. Rutledge, International Conference on Millimeter and Submillimeter Waves and Applications, San Diego, CA January 1994.

[29] "Active Grids for Quasi-Optical Power Combining," David Rutledge, US-Japan Workshop on Millimeter and Submillimeter Waves, Tsukuba, Japan, March 1994.

[30] "A 10-Watt X-band Grid Oscillator," Jonathan B. Hacker, Michael P. DeLisio, Moonil Kim, Cheh-Ming Liu, Shi-Jie Li, Scott W. Wedge, and David B. Rutledge, International Microwave Symposium, San Diego CA, May 1994.

[31] "Active Grids for Quasi-Optical Power Combining," David Rutledge, Workshop on Circuit Level Design and Modeling of Quasioptical Circuits and Systems, International Microwave Symposium, San Diego CA, May 1994.

[32] "Grid-Oscillator Beam-Steering Array," Shijie Li and David Rutledge, Antennas and Propagation International Symposium, Seattle WA, June 1994.

[33] *Grid Mixers and Power Grid Oscillators*, Ph.D. Thesis by Jonathan Hacker, Caltech, Pasadena, CA, 91125, 1994.

[34] "Terahertz Grid Frequency Doublers," Jung-Chih Chiao, Andrea Markelz, Yong-Jun Li, Jonathan Hacker, Thomas Crowe, James Allen, and David Rutledge, 6th International Symposium on Space Terahertz Technology, Pasadena CA, March, 1995.

[35] "A 100-Element MODFET Grid Amplifier," Michael P. De Lisio, Cheh-Ming Liu, Alina Moussessian, David Rutledge, and James J. Rosenberg, Antennas and Propagation Symposium, Newport Beach CA, June 1995.

[36] "Gain and Stability Models for HBT Grid Amplifiers," Cheh-Ming Liu, Emilio Sovero, Michael P. De Lisio, Alina Moussessian, James Rosenberg, and David Rutledge, Antennas and Propagation Symposium, Newport Beach CA, June 1995.

[37] "A 16-Element Tunnel Diode Grid Oscillator," Michael P. De Lisio, John F. Davis, Shi-Jie Li, and David Rutledge, Antennas and Propagation Symposium, Newport Beach CA, June 1995.

[38] "40-GHz Monolithic Grid Amplifier," Cheh-Ming Liu, Emilio Sovero, and David Rutledge, Submitted to *IEEE Microwave and Guided Wave Letters,* May, 1995.

[39] "Modelling and Performance of a 100-Element pHEMT Grid Amplifier," Michael DeLisio, Scott Duncan, Der-Wei Tu, Cheh-Ming Liu, Alina Moussessian, James Rosenberg, and David Rutledge, Submitted to *IEEE Transactions on Microwave Theory and Techniques* May, 1995.

STUDENTS

[1] Moonil Kim finished his thesis on the initial development of grid amplifiers and is now working at the Jet Propulsion Laboratory.

[2] Jon Hacker finished his thesis on grid mixers and high-power grid oscillators and currently working at Bell Communications Research.

[3] Michael De Lisio, an AASERT fellow, has been working on a 100-element MODFET grid amplifier and a 16-element tunnel-diode grid. In addition, Michael has been working on the 50-GHz monolithic millimeter-wave amplifier grid fabricated by Lockheed-Martin. He will be joining the University of Hawaii in the fall as an assistant professor.

[4] Victor Lubecke, an Hispanic student, is finishing his thesis on a 600-GHz tuning circuit, and will be joining JPL in the fall.

[5] Jung-Chih Chiao has demonstrated a grid-frequency doubler with an output power of 330 μW at 1 THz. He will be joining Bell Communications Research in the fall.

[6] Jeff Liu has been working on the monolithic 40-GHz amplifier grid fabricated by Rockwell International.

[7] John Davis, an African-American graduate student, has been working on the 16-element tunnel-diode grid. He is now working on high-efficiency switching power amplifiers.

[8] Shijie Li is working on a new high-gain quasi-optical grid amplifier that uses MIMIC amplifiers as the active components. The goal is to achieve single-stage gains of 20 dB.

[9] Polly Preventza is working on a 35-GHz InP oscillator grids using transistors provided by Mehran Matloubian at Hughes Research Labs in Malibu.

[10] Alina Moussessian is working with the Physical Optics Corporation to develop an electronic-beam steering system controlled by light.

ARMY INTERACTIONS

Dr. James Mink and I were co-editors of a special issue of the *IEEE Transactions on Microwave Theory and Techniques* on Quasi-Optical Techniques. This was published in October, 1993.

I attended a Workshop on Millimeter Wave Power Generation and Beam Control at the University of Alabama in Huntsville that was sponsored by the U.S. Army Missile command. I served on a panel that discussed quasi-optical oscillators.

I visited Fort Monmouth on several occaisions for to give seminars and to get advice. At Fort Monmouth I visited Jim Harvey, Arthur Paolella, Felix Schwering, and Barry Pearlman's group.

I have participated in bi-annual Quasi-Optical Alliance meetings at Lockheed-Martin that have often been attended by Jim Mink and Jim Harvey.

Industrial Interactions

We have ongoing collaborative efforts in monolithic amplifier grids with Lockheed-Martin Laboratories (Norm Byer and Sander Weinreb), the Jet Propulsion Laboratory (Peter Smith), and the Rockwell Science Center (Emilio Sovero and Aiden Higgins). We are also participating with Lockheed-Martin Corporation on their MAFET proposal, and met three times as part of their Quasi-Optical Alliance.

In addition, we have started a collaboration with Mehran Matloubian of Hughes Research Laboratories in Malibu CA to make millimeter-wave InP HEMT grid oscillators.

We collaborate on opto-electronic beam-steering with the Physical Optics Corporation (Lev Sadovnik) on an ARO SBIR.

ABSTRACTS

Submitted to *IEEE Transactions on Microwave Theory and Techniques*

Modelling and Performance of a 100-Element pHEMT Grid Amplifier

Michael P. De Lisio, Scott W. Duncan, Der-Wei Tu, Cheh-Ming Liu,
Alina Moussessian, James J. Rosenberg, and David B. Rutledge

***Abstract*—A 100-element hybrid grid amplifier has been fabricated. The active devices in the grid are custom-made pseudomorphic High Electron Mobility Transistor (pHEMT) differential-pair chips. We present a model for gain analysis and compare measurements with theory. The grid includes stabilizing resistors in the gate. Measurements show the grid has a peak gain of 10 dB when tuned for 10 GHz and a gain of 12 dB when tuned for 9 GHz. The maximum 3-dB bandwidth is 15% at 9 GHz. The minimum noise figure at 10 GHz is 3 dB. The maximum saturated output power at 9 GHz is 3.7 W, with a peak power-added efficiency of 12%. These results are a significant improvement over previous grid amplfiers based on Heterojunction Bipolar Transistors (HBT's). This is the first report of a full-size 100-element grid amplifier using HEMT devices.**

I. Introduction

Quasi-optical amplifiers combine the output powers of many solid-state devices in free space, eliminating the losses associated with waveguide or transmission-line combiners. The first quasi-optical amplifier was a 25-element grid amplifier [1]. A grid amplifier is an array of closely-spaced differential pairs of transistors. Fig. 1 shows the approach. A horizontally-polarized input beam excites rf currents on the input leads of the grid. This drives the transistor pair in the differential mode. Currents on the output leads produce a vertically-polarized output beam. Metal-strip polarizers provide independent tuning of the input and output circuits. Other types of quasi-optical amplifiers using amplifiers using patch antennas [2,3], back-to-back integrated horn antennas [4,5], folded slot antennas [6], and probe antennas [7] have been demonstrated. The largest number of devices have been incorporated in a 100-element HBT grid amplifier [8].

Manuscript submitted April 10, 1995. This research was supported by the Army Research Office and Martin Marietta Laboratories. M.P. De Lisio holds an NSF fellowship.

M.P. De Lisio, C.-M. Liu, A. Moussessian, and D.B. Rutledge are with the Department of Electrical Engineering, California Institute of Technology, Pasadena, CA 91125.

S.W. Duncan and D.-W. Tu are with Martin Marietta Laboratories, Baltimore, MD 21227–3898.

J.J. Rosenberg is with the Engineering Department, Harvey Mudd College, Claremont, CA 91711.

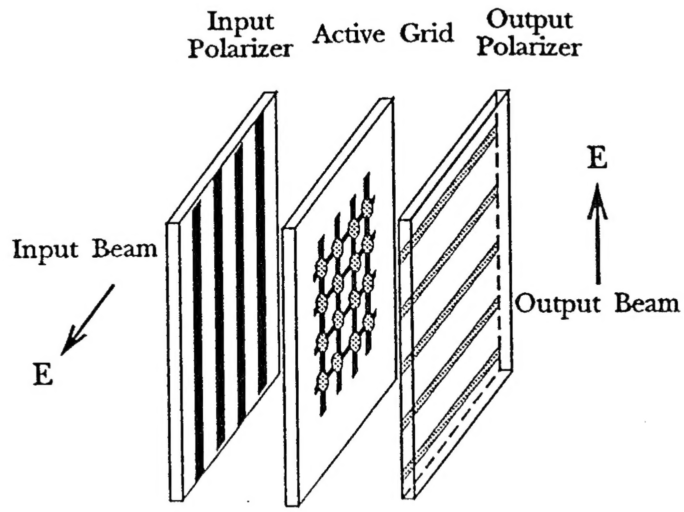

Fig. 1. A grid amplifier. A horizontally-polarized input beam is incident from the left. The output beam is vertically-polarized and is radiated to the right. The polarizers independently tune the output and input circuits.

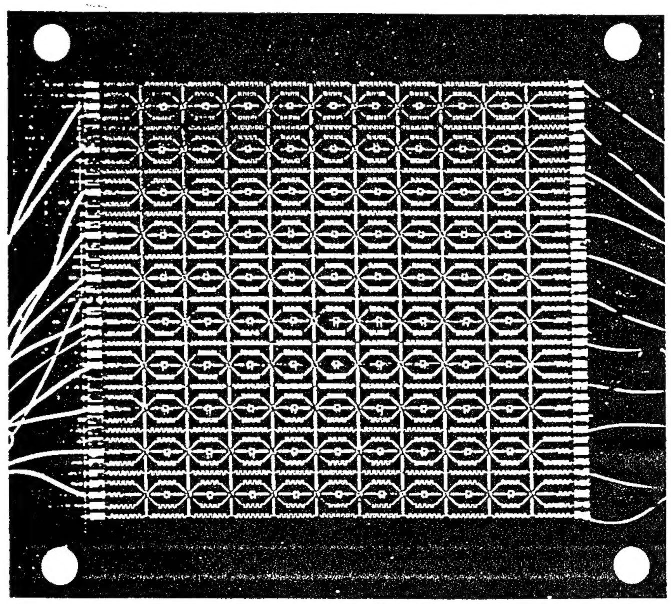

Fig. 2. Photograph of the amplifier grid. The grid is a 10×10 array of pHEMT differential pairs. The active area of the grid is 7.3 cm on a side.

Submitted to the *IEEE Microwave and Guided Wave Letters*

A 40-GHz Monolithic Grid Amplifier

Cheh-Ming Liu, Emilio A. Sovero, Wu Jing Ho, J. A. Higgins, and David B. Rutledge

***Abstract*—A 36-element monolithic grid amplifier has been fabricated. The peak gain is 4 dB at 40 GHz with a 3-dB bandwidth of 800 MHz. The active elements are pairs of heterojunction-bipolar-transistor's (HBT's). The individual transistors in the grid have a maximum oscillation frequency, f_{max}, of 100 GHz. The grid includes base stabilizing capacitors which result in a highly stable grid. This is the first report of a successful monolithic grid amplifier.**

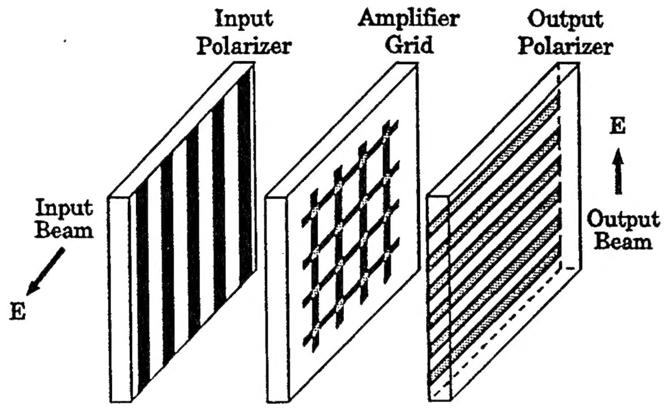

Fig. 1. A grid amplifier.

I. Introduction

A grid amplifier is a spatial power-combining device that amplifies a microwave beam and combines the outputs of many transistors, making it possible to greatly increase power [1-4]. Because the power is combined in free space, grid amplifiers eliminate losses associated with waveguides and transmission-line networks. Fig. 1 shows a perspective view of a grid amplifier. The input beam is on the left-hand side with horizontal polarization. The input beam is received by the amplifier grid, amplified, and then reradiated with vertical polarization, as the output beam to the right. The first grid amplifier, using MESFET's, showed a gain of 11 dB at 3.3 GHz [1]. Later, grid amplifiers also demonstrated gains of 10 and 11 dB at 10 GHz with HBT's [2,3], and 12 dB at 9 GHz with pHEMT's [4]. Other spatial-power combining approaches are actively being pursued [5-10]. Recently, Hubert, Schoenberg, and Popović demonstrated a quasi-optical millimeter-wave amplifier using slot antennas, with 6-dB gain flange-to-flange at 29 GHz [11]. These spatial power-combining amplifiers were fabricated by hybrid technology with chips mounted on a printed-circuit board. The grid-amplifier structure is planar with all the devices on one side, making this approach attractive for monolithic fabrication. Here we report the first monolithic grid amplifier with gain—4 dB at 40 GHz.

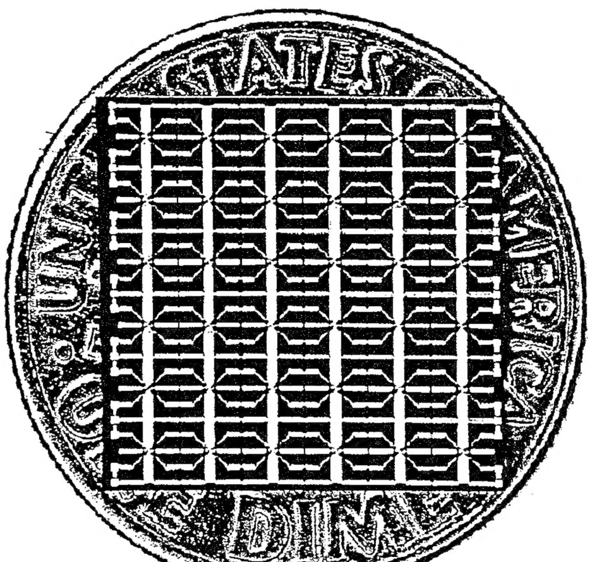

Fig. 2. Photograph of the 36-element monolithic grid amplifier compared with a dime.

The monolithic grid amplifier, shown in Fig. 2, is composed of 36 unit cells periodically distributed on a 565-μm GaAs substrate. The grid was fabricated with the HBT process established at Rockwell International [12]. The HBT under optimum bias(20 mA/transistor) has a maximum oscillation frequency, f_{max}, of 100 GHz and unity-current-gain frequency, f_t, of 60 GHz. The maximum available gain of an individual transistor at 40 GHz is 8.2 dB.

Manuscript submitted June 18, 1995. This research was supported by the Air Force Material Command/Rome Laboratory and the Army Research Office.

C.-M. Liu and D.B. Rutledge are with the Division of Engineering and Applied Science, California Institute of Technology, Pasadena, CA, 91125.

E.A. Sovero, W.J. Ho, and J.A. Higgins are with the Science Center, Rockwell International Corporation, 1049 Camino Dos Rios, Thousand Oaks, CA 91385.